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6. AUTHOR(S)

Zafer Gurdal

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Virginia Polytechnic Institute and State University
Departments of Aerospace and Ocean Engineering, and Engineering Science and Mechanics
Blacksburg, Virginia 24061-0219

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One objective of this project was to develop a global-local algorithm for wing structure design based on parallel genetic algorithms for the lower (local) level and homotopy algorithms for the upper (global) level. A second goal is to develop a similar procedure for aerodynamic wing design for a mocro aerial vehicle. The upper level optimization will use a response surface approximation quality of the response surface. In support of this main objective, new genetic algorithms and homotopy algorithm concepts will be expired.

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FINAL REPORT FOR AFOSR GRANTS F49620-96-1-[redacted]/0104

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WING STRUCTURAL DESIGN BY GENETIC ALGORITHMS AND HOMOTOPY METHODS

Period: 4/1/96 – 12/31/98

Zafer Gürdal
Departments of Aerospace and Ocean Engineering,
and Engineering Science and Mechanics
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061-0219
`gurdal@gurdal.esm.vt.edu`

Raphael T. Haftka
Department of Aerospace Engineering, Mechanics, and Engineering Science
University of Florida
Gainesville, FL 32611-6250
`haftka@ufl.edu`

Layne T. Watson
Departments of Computer Science and Mathematics
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061-0106
`ltw@cs.vt.edu`

March 26, 1999

Summary

The last annual report was just a few months before the final ending date of the project. This final report summarizes the project accomplishments during the period since the last annual report (9/1/98–12/31/98), and for the entire project. For reference, the two previous annual reports are attached as appendices.

Design of large and complex aircraft structures requires sizing of local details of stiffened panels in the wing (rib and skin panels) and fuselage. Details include stiffener shape and dimensions, stiffener spacing, and skin thickness. Such panels are increasingly being made of composite laminates, using layers of strong fibers embedded in flexible matrix material. The design of composite panels requires the specification of the stacking sequence (that is, the number of layers and their orientation) of each laminate, which involves discrete variables.

It is currently computationally impossible to design an entire wing or fuselage structure with all the panels optimized simultaneously. Instead, the overall design is performed with finite element models that typically have several thousand finite elements, each representing a large panel with local panel details smeared in terms of equivalent properties. These require the solution of tens of thousands of equations and, even with the smeared properties, each panel has several design variables leading to sizing problems with thousands of design variables and constraints. Modeling and optimizing the details will entail millions of equations for each analysis and tens of thousands of design variables.

One standard approach used in the aircraft industry for incorporating information on local structural detail during global sizing has been the use of "look-up tables," developed over time in each company. After each global sizing iteration performed using smeared panel representation, certain properties of the panels are matched with properties of designs that exist in a table of detailed panel designs. The table allows the overall design to gauge the sufficiency of the amount of material allocated to the panel for carrying the loads, and so provides the necessary link between the global and local design. However, the information provided in the tables is typically limited, incomplete, and often represents old designs. Consequently, when the wing optimization is completed, and panels are designed based on the final material distribution and loads, their designs are often substantially different from what is available in the look-up table. This, in turn changes the load distribution in the wing, which forces additional iterations of the overall optimization, a process which often does not converge.

Inspired by the above approach, we have developed under the grant a more rigorous approach to the same problem. We first perform a large number of panel optimizations for maximum failure load for various combinations of loadings and available amounts of material. We next fit a response surface (typically a quadratic or cubic polynomial) to the optimal failure loads of the panels. This response surface is incorporated in the global wing optimization, providing a constraint on panel load carrying capacity. If the response surface is accurate, we are guaranteed that we can find detailed panel designs that will match the overall wing design.

We first demonstrated the feasibility of this approach for wing design using continuous optimization for the stiffened panels (Ragon et al. [3]). This demonstration involved close work with George Tzong of McDonnell Douglas (now Boeing), Long Beach. This work coupled a wing design program, ADOP, used by McDonnell Douglas, to a panel design code, PASCO, developed by NASA.

We have also worked closely with Kumar Bhatia, of Boeing Seattle, to demonstrate the use of the same procedure with genetic algorithms for unstiffened panels in a fuselage structure. This second demonstration showed that genetic optimization is slowed down considerably by the constraints on detail panel design. Some of these constraints enforce compatibility with the global design, and some are inherent to the panel design itself.

To address these problems we have developed a permutation genetic algorithm that embodies the compatibility constraints with the wing design through its coding and other constraints through a phenome repair strategy (Liu etal. [1]). This has reduced the cost of the genetic optimization by two orders of magnitude. We have also explored the use of response surfaces and lamination parameters for reducing the cost of genetic optimization. (Todoroki and Haftka [4],[5],[6].) Wing design optimization using this approach was also demonstrated (Liu et al. [2]. It validated the use of response surfaces for integrating panel design by genetic optimization with overall wing design using continuous variables. We have also explored the use of advanced two-species genetic algorithms for integrating uncertainty in loading in the design process (Venter and Haftka [7]).

Several variations of genetic algorithms appropriate for composite structure design have been studied and a MPI standard based parallel version of the composite design genetic algorithm code (in FORTRAN 77) was developed. As a tool for later use in this project and by other researchers, an object-oriented parallel genetic algorithm code using migration and dynamic load balancing was developed. Very general genetic algorithm templates (written in Fortran 90) for composite material design have been written and tested. The object-oriented Fortran 90 templates provide a flexible data and operator infrastructure which can be easily adapted by users to test new genetic operators or evolutionary optimization mechanisms. Development of an MPI based parallel version of the Fortran 90 templates was completed, PASCO was converted to Fortran 90, and now the *entire analysis and parallel GA code exists in Fortran 90.* The parallel genetic algorithm work led to one MS thesis, and was published in two conference papers and two journal papers.

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Appendix A.

ANNUAL REPORT FOR AFOSR GRANTS F49620-96-1-0099/0104 and AASERT F49620-97-1-0342

WING STRUCTURAL DESIGN BY GENETIC ALGORITHMS AND HOMOTOPY METHODS

Period: 9/1/96 – 8/31/97

Zafer Gürdal
Departments of Aerospace and Ocean Engineering,
and Engineering Science and Mechanics
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061-0219
gurdal@gurdal.esm.vt.edu

Raphael T. Haftka
Department of Aerospace Engineering, Mechanics, and Engineering Science
University of Florida
Gainesville, FL 32611-6250
haftka@ufl.edu

Layne T. Watson
Departments of Computer Science and Mathematics
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061-0106
ltw@cs.vt.edu

March 26, 1999

Objectives.

One objective of this project is to develop a global-local algorithm for wing structure design based on parallel genetic algorithms for the lower (local) level and homotopy algorithms for the upper (global) level. A second goal is to develop a similar procedure for aerodynamic wing design for a micro aerial vehicle. The upper level optimization will use a response surface approximation of the lower level optima, with the homotopy parameter being related to the approximation quality of the response surface. In support of this main objective, new genetic algorithms and homotopy algorithm concepts will be explored.

Status of research.

Global-local approximation: Development of a global/local optimization scheme for wing design using a detailed-panel optimization code PASCO (Panel Analysis and Design Code) along with the global wing design program ADOP (Aeroelastic Design Optimization Program) of McDonnell Douglas was completed. The scheme was demonstrated for the design of a small generic un-tapered wing with a span of 350 *in* and 30° sweep angle. Four panels on the upper skin of the wing were designed based on optimal weight response surface constructed using local panel model with 12 J-stiffeners. The variables at the local level controlled the geometry detail of the stiffeners and the skin for designs with buckling and strength constraints. At the global level, design variables controlled the thickness of membrane finite elements which represented the wing panel skin and area of rod elements representing stringers without any structural details. Global constraints included stress constraints for all panels. Results of the study resulted in publication of a AIAA-SDM Conference paper jointly authored by McDonnell Douglas and Virginia Tech investigators. Near term goal of the activity is to expand the set of constraints in the problem by including global stiffness constraints, in terms of overall wing displacements, and aero-elastic constraint. In addition, comparison of the results presented by the authors will be made to results obtained by using more conventional design approaches. For a more complete evaluation, application of the current scheme to a more realistic large scale wing design problem will be sought.

In a parallel study, development of a new cost-effective nonlinear analysis capability for post-buckling analysis of local stiffened panels was initiated. The approach relies of expressing the postbuckling deformations in terms of a reduced set of basis vectors which are obtained from the derivatives of the nonlinear response with respect to the load path parameter. Once completed, the computational efficiency of the local panel optimization will make the global design of a wing structure including the nonlinear postbuckling characteristics of the local panels a possibility.

A permutation genetic algorithm that allows the upper level design to specify the number of plies in various orientations in the panel is being developed. With the number of plies of each orientation being fixed at the lower level, the lower-level design problem becomes a permutation optimization problem. Standard permutation genetic algorithms, developed mostly for the travelling salesman problem, are targetted at cyclical ordering rather than the linear order that characterizes a laminate. The 'gene-rank' algorithm, developed for laminate design, caters to the strong effect of gene position in the chromosome.

Parallel genetic algorithms: Several variations of genetic algorithms appropriate for composite structure design have been studied, and a MPI standard based parallel version of the composite design genetic algorithm code (in FORTRAN 77) has been developed. As a tool for later use in this project and by other researchers, an object-oriented parallel genetic algorithm code is being

developed. Very general genetic algorithm templates (written in Fortran 90) for composite material design have been written and tested. The object-oriented Fortran 90 templates provide a flexible data and operator infrastructure which can be easily adapted by users to test new genetic operators or evolutionary optimization mechanisms. Development of an MPI based parallel version of the Fortran 90 templates is the next step.

Response surface approximation: The response surface approximation is to be fit to the results of a large number of local optimizations. A small number of unconverged or otherwise faulty optimizations results can have large detrimental effects on the accuracy of the approximations. Consequently, we have focused our recent activity on the detection of such optimizations through method for finding outliers in response surfaces.

Micro aerial vehicle design: The first phase of the work is focusing on the identification and development of the analysis tools for aerodynamic flow analysis. Airfoil analysis programs based on linear panel method as well as Navier-Stokes equations have been evaluated, and the Navier-Stokes code is in the process of being modified to allow for transition from laminar to turbulent flow.

Accomplishments/new findings.

A methodology for simple and flexible yet efficient interface between large scale global design optimization codes and codes for local structural detail design has been developed. The approach was demonstrated using a McDonnell Douglas code ADOP (Aeroelastic Design Optimization Program) and the NASA local panel optimization code PASCO. The interface and the methodology were verified using a transport wing model specified by Dr. Tzong at McDonnell Douglas. Results of this study were presented in a paper at the AIAA/ASME/ASCE/AHS/ASC 38th SDM Conference: S. A. Ragon, Z. Gürdal, R. T. Haftka, and T. J. Tzong, "Global/local structural wing design using response surface techniques".

A study on improving the efficiency and reliability of a genetic algorithm for design optimization of composite laminates was completed. New selection schemes, called multiple elitist and variable elitist schemes, based on propagation of multiple designs (N_k of them) from the parent population to a child populations were introduced. For small values of N_k, a substantial increase in the richness of the final design populations and some decrease in the computational cost were observed while maintaining a high level of reliability. Acceptable levels of reliability could not be achieved when N_k became comparable to the population size.

A genetic algorithm for laminate design with fixed number of plies in all given orientation has been developed. The algorithms shows large improvement in reliability over standard genetic algorithms, and significant improvement over standard permutation genetic algorithm. A paper describing the algorithm by B. Liu, R.T. Haftka, and M. Akgün has been submitted for presentation to the AIAA/ASME/ASCE/AHS/ASC 39th SDM Conference.

The basic genetic algorithm data structures were extended to use multiple chromosomes (for structures with several different laminates such as wing boxes) and real variables (such as geometrical dimensions). The approach is implemented in the new object-oriented Fortran 90 code for the design of laminated composite panels. The multiple chromosome approach yields efficient and elegant code, and implementing crossover and mutation directly with real numbers is more effective than working with discrete binary approximations of real numbers.

The general approach used in the development of a nonlinear analysis of local panels is modelled after that described in the paper entitled "Two-Stage Rayleigh-Ritz Technique for Nonlinear

Analysis of Structures" by A.K. Noor, J.M. Peters, and C.M. Anderson. The purpose of this paper was to improve the efficiency of the conventional Rayleigh-Ritz technique by reducing the number of degrees of freedom of the discretized structure. In the present research, the two-stage Rayleigh-Ritz technique is applied to the problem of the geometrically nonlinear analysis of compressively loaded prismatic composite structures made of linked plate segments. Structures that may be analysed with this approach include stiffened aircraft panels and various thin-walled open and closed section columns used in various civil engineering applications. Here, the classical Rayleigh-Ritz technique of the first stage is replaced by a piecewise application of the Rayleigh-Ritz technique, which is commonly referred to as the finite strip method. The second stage of the technique is implemented by generating the appropriate path derivatives using the system equations generated by the finite strip analysis. The expressions for the path derivatives are obtained by differentiating the equilibrium equations.

Results generated so far are for a flat simply supported composite plate loaded by a uniform end shortening. For purposes of the finite strip analysis, the plate was modelled using four finite strips across the width. Three different assumed imperfection amplitudes are considered. In all three cases, the imperfection shape was assumed to be a half sine wave in both the length and width directions. Results of the reduced basis finite strip solution agreed well with the full finite strip solution and those presented in literature based on other methods

Personnel supported.

Faculty supported by the grant are Z. Gürdal, R. T. Haftka, and L. T. Watson. Graduate students supported by the grant are Matthew McMahon (Virginia Tech) and Boyang Liu (Florida). The AASERT portion supports graduate student Jason Sloan, and undergraduate assistant Thomas Samara.

Graduate students associated with the grant include Denitza Krasteva, Maria Sosonkina, Christina Perry, Scott A. Ragon, Grant Soremekun, and Gerhard Venter.

Visiting Scholars associated with the grant include Professor Akira Todoroki of the Tokyo Institute of Technology and Professor Mehmet Akgün of Middle Eastern Technical University in Turkey.

Publications.

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V. V. Vasiliev, and Z. Gürdal, "On general concepts of structural design," *Proc. of the First International Conference on Composite Science and Technology (ICCST/1)*, Durban, South Africa, 1996, 565–570.

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A. C. Perry, Z. Gürdal, and J. H. Starnes, Jr., "Minimum weight design of compressively loaded stiffened panels for postbuckling response," *Engineering Optimization.*

Y. Ge, L. T. Watson, and E. G. Collins, Jr., "Cost-effective parallel processing for H^2/H^∞ controller synthesis", *Internat. J. Systems Sci.*.

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S. Suherman, R. H. Plaut, L. T. Watson, and S. Thompson, "Effect of human response time on rocking instability of a two-wheeled suitcase", *J. Sound Vibration.*

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A. A. Giunta, O. Golovidov, D. L. Knill, B. Grossman, W. H. Mason, L. T. Watson, and R. T. Haftka, "Multidisciplinary design optimization of advanced aircraft configurations", in *Lecture Notes in Physics*, Springer-Verlag, Berlin.

J. F. Rodríguez, J. E. Renaud, and L. T. Watson, "Convergence of trust region augmented Lagrangian methods using variable fidelity data", in *Proc. Second World Congress on Structural and Multidisciplinary Optimization*, Zakopane, Poland, 1997.

Journal articles submitted during the grant period are:

M. C. Cowgill, R. J. Harvey, and L. T. Watson, "A genetic algorithm approach to cluster analysis", *Comput. Math. Appl.*.

A. P. Morgan, L. T. Watson, and R. A. Young, "A Gaussian derivative based version of JPEG for image compression and decompression", *IEEE Trans. Image Processing*.

Y. Ge, L. T. Watson, and E. G. Collins, Jr., "An object-oriented approach to semidefinite programming", *Math. Comput. Appl.*.

M. Sosonkina, L. T. Watson, and R. K. Kapania, "A new adaptive GMRES algorithm for achieving high accuracy", *Numer. Linear Algebra Appl.*.

Y. Wang, D. S. Bernstein, and L. T. Watson, "Convergence theory of probability-one homotopies for model order reduction", *Automatica*.

D. Haim, A. A. Giunta, M. M. Holzwarth, W. H. Mason, L. T. Watson, and R. T. Haftka, "Suitability of optimization packages for an MDO environment", *Engrg. Comput.*.

G. Soremekun, Z. Gürdal, R. T. Haftka, and L. T. Watson, "Improving genetic algorithm efficiency and reliability in the design and optimization of composite structures", *Comput. Methods Appl. Mech. Engrg.*.

J. F. Rodríguez, J. E. Renaud, and L. T. Watson, "Trust region augmented Lagrangian methods for sequential response surface approximation and optimization", *ASME J. Mech. Design*.

R. H. Plaut, S. Suherman, D. A. Dillard, B. E. Williams, and L. T. Watson, "Deflections and buckling of a bent elastica in contact with a flat surface", *Internat. J. Solids Structures*.

O. B. Golovidov, W. H. Mason, B. Grossman, L. T. Watson, and R. T. Haftka, "Response surface approximations for aerodynamic parameters in high speed civil transport optimization", *J. Aircraft*.

J. F. Rodríguez, J. E. Renaud, and L. T. Watson, "Convergence of trust region augmented Lagrangian methods using variable fidelity approximation data", *Structural Optim.*.

Interactions/transitions.

Conference presentations were:

Approximation Workshop, ICASE, NASA Langley Research Center, Hampton, VA, August, 1996.

Sixth AIAA/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, Sept., 1996 (5 papers).

Society of Engineering Science 33rd Annual Technical Meeting, Tempe, AZ, October, 1996.

INFORMS, Atlanta, GA, Nov., 1996.

35th IEEE Conference on Decision and Control, Kobe, Japan, December, 1996.

8th SIAM Conference on Parallel Processing for Scientific Computing, Minneapolis, MN, March, 1997.

38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Kissimmee, FL, April, 1997.

Second World Congress on Structural and Multidisciplinary Optimization, Zakopane, Poland, May, 1997.

1997 American Control Conference, Albuquerque, NM, June, 1997.

SIAM Annual Meeting, Stanford, CA, July, 1997.

Workshop on Approximation and Surrogates, ICASE, NASA Langley Research Center, Hampton, VA, July, 1997.

ASME Design Automation Conference, Sacramento, CA, Sept., 1997.

Consultative and advisory work:

There is ongoing research interaction with the Structural Mechanics Branch of NASA Langley Research Center, Hampton, VA. Principal NASA contacts are Dr. James H. Starnes, Jr. (Branch Head) for tailoring of composite structures for aircraft, and Marvin Rhodes for tailoring of composite panels for space structures.

Technology transitions or transfer:

PERFORMER
Layne T. Watson, Virginia Polytechnic Institute & State University
Telephone: 540-231-7540
CUSTOMER
General Motors Research and Development Center
Warren, MI
Contact: Alexander P. Morgan, 810-986-2157
RESULT
Homotopy algorithms; mathematical software
APPLICATION
Linkage mechanism design; combustion chemistry; robotics; CAD/CAM

PERFORMER
Layne T. Watson, Virginia Polytechnic Institute & State University
Telephone: 540-231-7540
CUSTOMER
Lucent Technologies
Murray Hill, NJ
Contact: Robert Melville, 908-582-2420
RESULT
Homotopy algorithms; mathematical software
APPLICATION
Circuit design and modelling

PERFORMER
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 540-231-5905
CUSTOMER
Northrop-Grumman, Aircraft Division
Hawthorne, CA 90250
Contact: Dr. Robert P. Ley, 310-332-1305
RESULT
Design optimization tool based on STAGS finite element code
APPLICATION
Optimum design of aircraft fuselage shells with rings, stiffeners, and cutouts

PERFORMER
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 540-231-5905
CUSTOMER
Sikorsky Aircraft
Stratford, Connecticut 06497
Contact: Christos Kassapoglou, 203-386-3292
RESULT
Computer code for efficient analysis and design of grid-stiffened panels
APPLICATION
Combined structural and cost optimization of helicopter tub panels

PERFORMER
Zafer Gürdal
Virginia Polytechnic Institute & State University
Telephone: 540-231-5905 / 540-231-6262
CUSTOMER
Boeing Defense & Space Group, Helicopter Division
Philadelphia, PA
Contact: Deny Rock, 610-591-3848
RESULT
Analysis tools for variable stiffness panels under combined loads
APPLICATION
Design of aircraft panels based on advanced tow-placement technology

PERFORMER
Raphael T. Haftka, University of Florida
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 352-392-9595 / 540-231-5905
CUSTOMER
McDonnell Douglas Aerospace
Long Beach, CA
Contact: Dr. George Tzong, 310-497-5050
RESULT
Engineering design tool, ADOP + PASCO
APPLICATION
Global/local design of aircraft wing structures

PERFORMER
Raphael T. Haftka, University of Florida
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 352-392-9595 / 540-231-5905
CUSTOMER
Boeing Computer Services
Huntsville, AL
Contact: Al Underbrink / George P. Williams, Jr., 205-461-2950
RESULT
Installed a genetic optimization code for Huntsville
APPLICATION
Optimal design of racks made of composite laminates for space station

PERFORMER
Raphael T. Haftka, University of Florida
Telephone: 352-392-9595
CUSTOMER
Ford Motor Company
Dearborn, MI
Contact: Dr. Mehran Chirehdast, 313-390-5201
RESULT
Demonstrated application of response surface technology to automotive problems
APPLICATION
Optimal design of automotive structures for increased fatigue life

Inventions or patents.

None.

Honors/awards.

AIAA Fellow: Raphael T. Haftka.

IEEE Fellow: Layne T. Watson.

Best Paper Award, Sixth AIAA/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Haftka and Watson.

Appendix B.

ANNUAL REPORT FOR AFOSR GRANTS F49620-96-1-0099/0104 and AASERT F49620-97-1-0342

WING STRUCTURAL DESIGN BY GENETIC ALGORITHMS AND HOMOTOPY METHODS

Period: 9/1/97 – 8/31/98

Zafer Gürdal
Departments of Aerospace and Ocean Engineering,
and Engineering Science and Mechanics
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061-0219
gurdal@gurdal.esm.vt.edu

Raphael T. Haftka
Department of Aerospace Engineering, Mechanics, and Engineering Science
University of Florida
Gainesville, FL 32611-6250
haftka@ufl.edu

Layne T. Watson
Departments of Computer Science and Mathematics
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061-0106
ltw@cs.vt.edu

March 26, 1999

Objectives.

The primary objective of this project is to develop a global-local algorithm for wing structure design based on parallel genetic algorithms for the lower (local) level and constrained optimization algorithms for the upper (global) level. A second goal is to develop a similar procedure for combined aerodynamic-control wing design for a micro aerial vehicle. The proposed approach is to use response surface approximations of the lower level optima during the upper level optimization process, with a strategy for managing varying fidelity approximations. In support of the main objective, new genetic algorithms and optimization concepts, and cost effective panel analysis algorithms are explored to increase the efficiency and reliability of the local level optimizations.

Status of research.

Global-local approximation: Development of a global/local optimization scheme for wing design using a detailed-panel optimization code PASCO (Panel Analysis and Design Code) along with the global wing design program ADOP (Aeroelastic Design Optimization Program) of McDonnell Douglas was reported in the previous grant period. During the present grant period, modifications were implemented to generalize the process so that it can be applied to similar aircraft design problems with different local design requirements and local details. In particular, the global/local design work pursued during the past 12 months focused on the development of a response surface technique for a High Speed Commercial Transport (HSCT) fuselage configuration. This work was part of one of the investigator's assignment during his sabbatical leave from Virginia Tech. Prof. Gürdal spent 9 months at Boeing Commercial Aircraft in Seattle working with one of the Boeing engineers, Mr. J. Lynn Henderson, to initiate the global/local design approach.

The approach used is similar to the one described in the previous progress report, and makes use of a coarse modeling of the global fuselage structure with the local panels represented as smeared elements. The design variables, at this level, control the thickness of membrane finite elements, which represented the wing panel skin, and area of rod elements representing stringers without any structural details. Global constraints included stress constraints for all panels. In the previous implementation with formerly McDonnell Douglas, a company specific finite element code `ADOP` was used as the global optimizer. In the present implementation, a commercial finite element based design optimization code `GENESIS` developed by VMA Engineering (Garry Vanderplats) was used for global sizing.

In addition to the stress constraints, in the present work there are constraints imposed on the relative percentage of the thicknesses of layers with different orientation angles. These constraints are Boeing specific and taken into account during the local panel optimization implementation. A more significant difference of the present implementation from the wing design study performed earlier is the nature of the local panel analysis. The stiffened panels in the previous study were sized using a linear bifurcation buckling analysis called `PASCO` (Panel Analysis and Sizing Code) developed at NASA. The fuselage panels designed against buckling are unacceptably heavy and, hence, they must be designed to operate in a postbuckled state prior to ultimate failure loads. Analysis and optimization of panels for postbuckling performance requires use of a geometrically nonlinear analysis, which is typically much more expensive than the linear buckling analysis.

Geometrically nonlinear analysis of local panels: In a parallel study two approaches to the geometrically nonlinear local panel analysis, namely "full" and "reduced basis" finite strip analyses, were investigated. The "full" analysis method is a nonlinear finite strip analysis of the semi-analytical multi-term type. Displacement fields are approximated in the longitudinal direction using

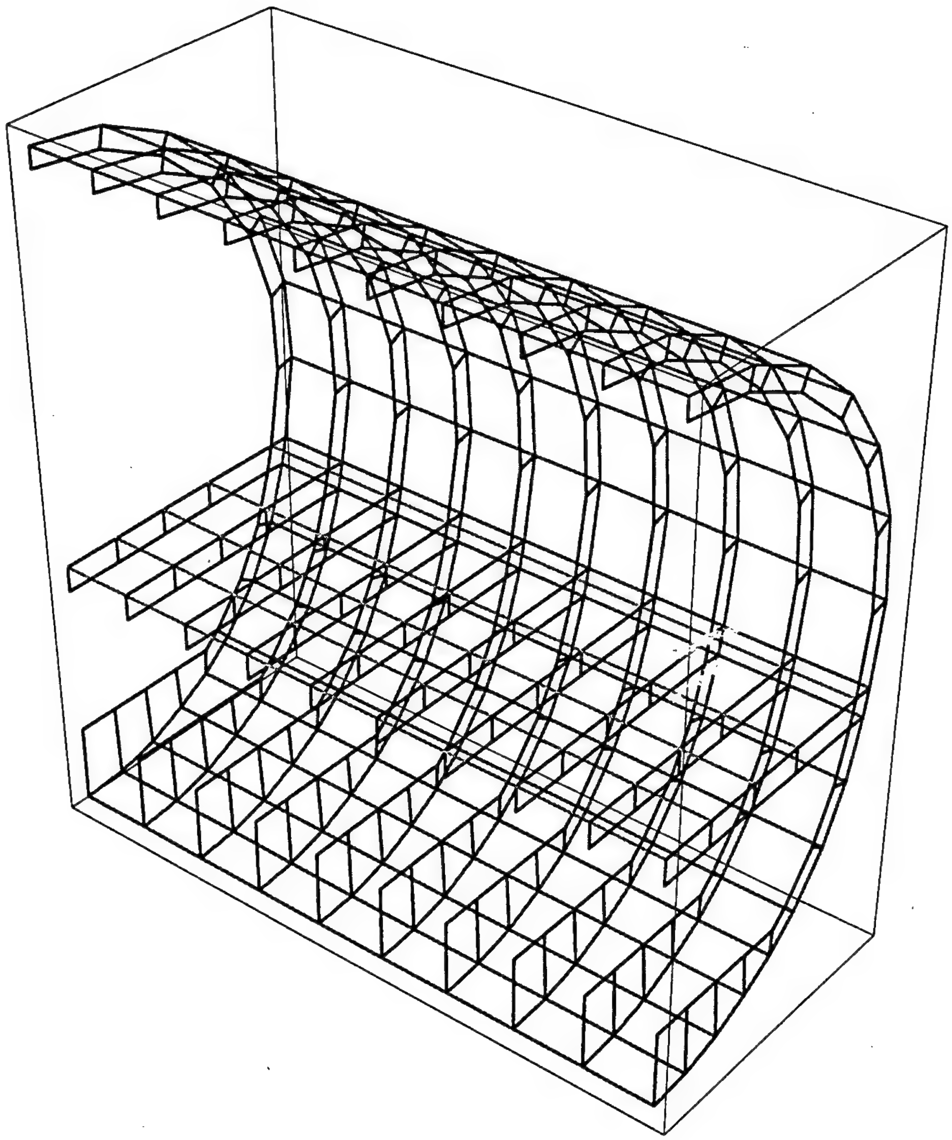
trigonometric series and using cubic polynomials in the transverse direction. Individual finite strips are modeled as balanced and symmetric laminated composite materials, and the resulting structure may be loaded bi-axially. The boundary conditions at the loaded ends are simply supported out-of-plane, while a variety of in-plane and out-of-plane boundary conditions may be modeled at the unloaded edges. Geometric shape imperfections are permitted. The alternate "reduced" scheme, makes use of a reduced basis method in conjunction with the foregoing finite strip analysis. Here, the (potentially large) set of nonlinear algebraic equations produced by the finite strip method are replaced by a small set of system equations. In the present implementation, the basis vectors consist of successive derivatives of the nonlinear system equations with respect to the loading parameter, λ. A weighted norm of the full residual vector, e, is used to determine whether or not to generate a new set of basis vectors. If this norm is greater than a user specified tolerance, $\hat{e}$, a new set of basis vectors is generated before proceeding with the solution procedure; otherwise, the reduced solution procedure continues with the current set of basis vectors.

Genetic algorithms for local panel design: A permutation genetic algorithm that allows the upper level design to specify the number of plies in various orientations in the panel has been developed. With the number of plies of each orientation being fixed at the lower level, the lower-level design problem becomes a permutation optimization problem. Standard permutation genetic algorithms, developed mostly for the traveling salesman problem, are targeted at cyclical ordering rather than the linear order that characterizes a laminate. The 'gene-rank' algorithm, developed for laminate design, caters to the strong effect of gene position in the chromosome. In addition to permutation coding, repair techniques proved to be powerful for allowing efficient use of the genetic algorithm. The results have been reported in a conference paper and submitted to a journal for publication.

Parallel genetic algorithms: Several variations of genetic algorithms appropriate for composite structure design have been studied and a MPI standard based parallel version of the composite design genetic algorithm code (in FORTRAN 77) was developed. As a tool for later use in this project and by other researchers, an object-oriented parallel genetic algorithm code was developed. Very general genetic algorithm templates (written in Fortran 90) for composite material design have been written and tested. The object-oriented Fortran 90 templates provide a flexible data and operator infrastructure which can be easily adapted by users to test new genetic operators or evolutionary optimization mechanisms. Development of an MPI based parallel version of the Fortran 90 templates was completed, PASCO was converted to Fortran 90, and now the *entire analysis and parallel GA code exists in Fortran 90.*

Response surface approximation: The response surface approximation is to be fit to the results of a large number of local optimizations. A small number of unconverged or otherwise faulty optimizations results can have large detrimental effects on the accuracy of the approximations. Consequently, we have focused our recent activity on the detection of such optimizations through methods for finding outliers in response surfaces.

Micro aerial vehicle design: The first phase of the work focused on the identification and development of the analysis tools for aerodynamic flow analysis. Airfoil analysis programs based on the linear panel method as well as the Navier-Stokes equations have been evaluated, and the Navier-Stokes code was modified to allow for the transition from laminar to turbulent flow. Extensive studies of wing and airfoil design with response surface techniques have been carried out. These revealed that these two design elements are not good candidates for bilevel optimization. On the other hand, input from industry (Lockheed Martin and Aerovironment) indicated to us that the problem of aerodynamic and control design are very important for micro aerial vehicles. Consequently we are shifting to consideration of this problem.



Accomplishments/new findings.

Global-local design: Instead of using the entire airplane model, a segment of the fuselage shown in the figure is used as the global model. This simplification enables us to investigate the important characteristics of the response surface technique without the computational burden of analyzing the entire structure.

The software tool selected for the construction of the response surface is a Boeing internal code "Design and Analysis of Computer Experiments Package (DACEPAC)". For specified bounds and number of levels that can be used for the design, the DACEPAC software computes a series of design points based on orthogonal arrays. The software allows the user to choose among several orthogonal arrays with varying numbers of runs and numbers of levels for the design variables. This choice is usually based on how computationally expensive the local sizing is.

Demonstration of the global/local approach has been performed by simulating the current sizing approach used at Boeing with strength and ply percentage constraints. Four design variables which represent the thicknesses of the 0-, 45-, and 90-degree layers in the skin elements (t_0, t_{45}, and

t_{90}, respectively) and the thickness of a 0-degree smeared stiffener are currently used during a global optimization cycle. The fuselage segment show in the figure is sub-divided into 12 design variable zones (DV-zones). For each DV-zone included in the global model, a strength constraint based on strain failure of the individual layers within each element of the DV-zone is used. Although there is one strength constraint per DV-zone, GENESIS internally monitors the strains in each element within the DV-zone and each layer in a given element. In addition to the strength constraint additional constraints that represent the limitations on the laminate ply percentages (percent of plies with different orientations) are imposed. Therefore, even though there are only 12 DV-zones used in the current fuselage segment, a very large number of constraints (near 9,000 constraints) are monitored during the design optimization iterations.

Since all of these constraints are local to the design variable zones used in the model, it is possible to replace all of them with a single weight margin constraint per DV-zone represented by a response surface. The advantage of such an approach will be the reduction of the number of constraints used during the global sizing. In this particular case of a fuselage segment, the reduction may not be substantial. However, considering that the full airplane model includes more than 700,000 constraints, most of which are the strength constraints in the elements, any reduction in this number would make an impact on the computational effort to find the minimum weight design.

Therefore, the first step is to construct a response surface that included the strength constraint and the five ply percentage constraints for this section of the fuselage. Since none of these constraints includes information about the size and shape of the elements, and all of them are applicable at any point in the section of the structure under consideration, there is no need for multiple response surfaces. In fact, if the set of ply percentage constraints remain the same, one response surface may be enough to represent the strength constraints over the entire airplane model.

The interface for the response surface constructed for this purpose includes the usual three stress resultants (N_x, N_y, and N_{xy}) and the three stiffness requirements (A_{11}, A_{22}, and A_{66}). The skin laminate stacking sequence and its thickness are the design variables for the local optimization for building the response surface. The smeared stiffener thickness is added to the thickness of the 0-degree layers during the local optimization. However, it should be noted that existence of thickness percentage constraints between the skin and the stiffener would have forced us to use a different strategy for the local optimization requiring the treatment of the smeared stiffener thicknesses as independent variables.

One of the important elements of the process was the interface routine that maintained the interaction of the global design iterations and the local response surface. Since each design zone is composed of multiple number of elements with different stresses, and the entire design variable zone is composed of one laminate thickness distribution, the determination of the optimal thickness for the zone required determination of the most critical stress state. In the traditional approach this was accomplished by GENESIS computing the stress constraints in each element and adding the appropriate number of internal constraints during the optimization cycles. With the response surface approach, the task of ensuring that the constraint is computed at the most critical element in the zone was handled by the interface routine. That is, the stress resultants in each element in a given design variable zone is passed to the interface routine. The interface program calls the response surface for each stress state to compute the weight margin constraint, and uses the most critical one as the constraint for that design variable zone.

Genetic algorithms for local panel design: A genetic algorithm for laminate design with a fixed number of plies in all given orientations has been developed. The algorithm shows a large improvement in reliability over standard genetic algorithms, and significant improvement over the standard permutation genetic algorithm. A paper describing the algorithm by B. Liu, R.T. Haftka, and M. Akgün has been presented at the AIAA/ASME/ASCE/AHS/ASC 39th SDM Conference and submitted to Computer Methods in Applied Mechanics and Engineering for publication.

The basic genetic algorithm data structures were extended to use multiple chromosomes (for structures with several different laminates such as wing boxes) and real variables (such as geometrical dimensions). The approach is implemented in the new object-oriented Fortran 90 code for the design of laminated composite panels. The multiple chromosome approach yields efficient and elegant code, and implementing crossover and mutation directly with real numbers is more effective than working with discrete binary approximations of real numbers.

Nonlinear local panel analysis: Computational efficiencies of the two approaches to the local panel analysis were studied. Depending on the nature of the problem, the reduced solution procedure was found to offer computational savings of 20–60% compared to the full solution procedure. For any given analysis performed with the full solution method, there are two major tasks which take up most of the CPU time: (1) the factorization of the assembled system matrices and (2) the formation of the strip level nonlinear stiffness matrices. The reduced solution method can significantly reduce the number of times that the (full) system matrices must be factored, but has no effect on the number of times in which the local stiffness matrices are formed. As a consequence, the reduced method is most effective in reducing the computational cost of the full method when the most significant portion of the cost of the original (full) problem is matrix factorization. In particular, the ratio, C_f, of the cost of matrix factorization to the cost of matrix formation is a significant indicator of the potential effectiveness of the reduced solution procedure. If this ratio (for the full problem) is large (> 1), the reduction in the cost of factorization will offset the costs of generating basis vectors, and the reduced solution procedure will be effective in reducing the overall computational cost. In general, a larger C_f will lead to larger computational savings. If, on the other hand, C_f (for the full problem) is small (≤ 1), the reduction in factorization costs will be offset by the costs of generating basis vectors, and the reduced method will be as costly (or more costly) compared to the full solution method. In general, then, the reduced solution method is most effective for problems with large numbers of finite strips. As the number of finite strips is increased, the cost of forming the local stiffness matrices increases linearly, while the factorization cost of the global stiffness matrix increases at a greater rate. The addition of longitudinal terms increases the costs of both the full and reduced solution procedures, but has little effect on their relative efficiencies.

In addition to the above considerations, the efficiency and robustness of the reduced solution method was found to be sensitive to the user specified error norm, $\hat{e}$, used during the solution procedure to determine when to generate new basis vectors. If $\hat{e}$ is too large, new sets of basis vectors are not generated when they are needed and the solution procedure either diverges or generates erroneous results. If $\hat{e}$ is too small, new sets of basis vectors are generated more often than they are needed, and the computational cost of the solution procedure increases. There is no fixed value for $\hat{e}$ that is best for all problems, although $\hat{e} = 0.010$ appears to be a reasonable initial guess. The full solution procedure was found to be very robust for all the examples considered.

The robustness and cost-effectiveness of the nonlinear stiffened panel analysis program makes it an ideal tool for use in the design not only of stiffened panels but also in the design of large

structures with many connected panels such as the global/local design problem being studied in the present research.

Parallel genetic algorithms: The parallel GA code implemented migration between subpopulations (evolving independently on different processors), and the parallel, dynamically adapting algorithm resulted in both better reliability and reduced normalized cost compared to a static serial algorithm with migration. The parallel implementation used dynamic load balancing, fully distributed control, and a sophisticated termination detection algorithm. The surprising finding was that nondeterminism in the parallel task management significantly enhanced the performance of the (already nondeterministic) GA and migration. One interpretation of this finding is that random migration is superior to a fixed migration pattern. The parallel code also scaled very well, showing no significant communication penalty with 64 processors.

Personnel supported.

Faculty supported by the grant are Z. Gürdal, R. T. Haftka, and L. T. Watson. Professor W. Shyy of the University of Florida is participating without support. Graduate students supported by the grant are Matthew McMahon and Scott A. Ragon (Virginia Tech), and Boyang Liu (Florida). McMahon at Virginia Tech was assisted by an undergraduate research project student Michael Davis. The AASERT portion supports graduate student Jason Sloan, and undergraduate assistant Thomas Samara.

Graduate students associated with the grant include Denitza Krasteva, Maria Sosonkina, Grant Soremekun, and Gerhard Venter.

Visiting Scholars associated with the grant include Professor Akira Todoroki of the Tokyo Institute of Technology, Professor Mehmet Akgün of Middle Eastern Technical University in Turkey, and Dr. Itsuro Kajiwara of the Tokyo Institute of Technology.

Publications.

Journal articles published during the grant period are:

Y. Ge, L. T. Watson, and E. G. Collins, Jr., "Cost-effective parallel processing for H^2/H^∞ controller synthesis", *Internat. J. Systems Sci.*, 28 (1997) 1069–1076.

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Refereed conference papers published during the grant period are:

A. A. Giunta, O. Golividov, D. L. Knill, B. Grossman, W. H. Mason, L. T. Watson, and R. T. Haftka, "Multidisciplinary design optimization of advanced aircraft configurations", in *Lecture Notes in Physics 490, Proc. Fifteenth Internat. Conf. on Numerical Methods in Fluid Dynamics*, P. Kutler, J. Flores, and J.-J. Chattot (eds.), Springer-Verlag, Berlin, 1998, 14–34.

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S. L. Burgee and L. T. Watson, "The promise (and reality) of multidisciplinary design optimization", in *Large-Scale Optimization with Applications, Part II: Optimal Design and Control*, L. T. Biegler, T. F. Coleman, A. R. Conn, and F. N. Santosa (Eds.), Springer-Verlag, New York, 1997, 301–324.

D. L. Knill, A. A. Giunta, C. A. Baker, B. Grossman, W. H. Mason, R. T. Haftka, and L. T. Watson, "HSCT configuration design using response surface approximations of supersonic Euler aerodynamics", 36th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, AIAA Paper 98–0905, 1998, 1–23.

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M. T. McMahon, L. T. Watson, G. A. Soremekun, Z. Gürdal, and R. T. Haftka, "A Fortran 90 genetic algorithm module for design of composite laminate structures", in *Structural Optimisation*, G. P. Steven, O. M. Querin, H. Guan, and Y. M. Xie (Eds.), Oxbridge, Victoria, Australia, 1998, 95–102.

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M. C. Cowgill, R. J. Harvey, and L. T. Watson, "A genetic algorithm approach to cluster analysis", *Comput. Math. Appl.*, to appear.

A. P. Morgan, L. T. Watson, and R. A. Young, "A Gaussian derivative based version of JPEG for image compression and decompression", *IEEE Trans. Image Processing*, to appear.

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J. F. Rodríguez, J. E. Renaud, and L. T. Watson, "Convergence of trust region augmented Lagrangian methods using variable fidelity approximation data", *Structural Optim.*, to appear.

L. T. Watson, S. Suherman, and R. H. Plaut, "Two-dimensional elastica analysis of equilibrium shapes of single-anchor inflatable dams", *Internat. J. Solids Structures*, to appear.

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M. T. McMahon, L. T. Watson, G. A. Soremekun, Z. Gürdal, and R. T. Haftka, "A Fortran 90 genetic algorithm module for composite laminate structure design", *Engrg. Computers*, to appear.

D. L. Knill, A. A. Giunta, C. A. Baker, B. Grossman, W. H. Mason, R. T. Haftka, and L. T. Watson, "Response surface models combining linear and Euler aerodynamics for HSCT design", *J. Aircraft*, to appear.

L. L. Henderson, Z. Gürdal, and A. Loos, "Combined structural and manufacturing optimization of stiffened composite panels", *J. Aircraft*, to appear.

Refereed conference papers accepted during the grant period are:

L. T. Watson, "Globally convergent homotopy methods", in *Encyclopedia of Optimization*, C. A. Floudas and P. M. Pardalos (Eds.), Kluwer, Norwell, MA, 1998.

L. T. Watson, "Multidisciplinary design optimization", in *Encyclopedia of Optimization*, C. A. Floudas and P. M. Pardalos (Eds.), Kluwer, Norwell, MA, 1998.

J. E. Renaud, J. F. Rodríguez, and L. T. Watson, "Convergence using variable fidelity approximation data in a trust region managed augmented Lagrangian approximate optimization", AIAA Paper 98–4801, in *Proc. 7th AIAA/USAF/NASA/ISSMO Symp. on Multidisciplinary Analysis and Optimization*, St. Louis, MO, 1998.

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V. O. Balabanov, R. T. Haftka, B. Grossman, W. H. Mason, and L. T. Watson, "Multifidelity response surface model for HSCT wing bending material weight", AIAA Paper 98–4804, in *Proc. 7th AIAA/USAF/NASA/ISSMO Symp. on Multidisciplinary Analysis and Optimization*, St. Louis, MO, 1998.

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M. Elseifi, Z. Gürdal, and E. Nikolaidis, "Effects of probabilistic variations in manufacturing variables on process-induced imperfections in laminated composites", AIAA Paper 98–4841, in *Proc. 7th AIAA/USAF/NASA/ISSMO Symp. on Multidisciplinary Analysis and Optimization*, St. Louis, MO, 1998.

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M. S. Cramer, B. B. Lowekamp, and L. T. Watson, "Analytical and numerical solutions for nonlinear thermal square waves", *Internat. J. Heat Mass Transfer*.

Y. Wang, D. S. Bernstein, and L. T. Watson, "Convergence theory of probability-one homotopies for model order reduction", *Internat. J. Robust Nonlinear Control*.

D. Haim, A. A. Giunta, M. M. Holzwarth, W. H. Mason, L. T. Watson, and R. T. Haftka, "Comparison of optimization software packages for an aircraft multidisciplinary design optimization problem", *Design Optim.*.

G. Soremekun, Z. Gürdal, R. T. Haftka, and L. T. Watson, "Composite laminate design by genetic algorithm with generalized elitist selection", *J. Composite Materials*.

O. B. Golovidov, W. H. Mason, B. Grossman, L. T. Watson, and R. T. Haftka, "Response surface approximations for aerodynamic parameters in high speed civil transport optimization", *J. Aircraft*.

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M. Sosonkina, D. C. S. Allison, and L. T. Watson, "Parallel cost analysis of adaptive GMRES implementations for homotopy methods", *SIAM J. Matrix Anal.*.

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G. Mateescu, C. J. Ribbens, and L. T. Watson, "A domain decomposition algorithm for Hermite collocation problems", *SIAM J. Sci. Comput.*.

M. T. McMahon and L. T. Watson, "A distributed genetic algorithm with migration for the design of composite laminate structures", *Parallel Algorithms Appl.*.

M. Elseifi, Z. Gürdal, and E. Nikolaides, "Convex and probabilistic models of uncertainties in geometric imperfections of stiffened composite panels", *AIAA J.*.

Interactions/transitions.

Conference presentations were:

ASME Design Automation Conference, Sacramento, CA, Sept., 1997.

Sixth SIAM Conference on Applied Linear Algebra, Snowbird, UT, October, 1997.

Fifth International Panel and Engineered-Wood Technology Conference and Exposition, Atlanta, GA, October, 1997.

36th AIAA Aerospace Sciences Meeting, Reno, NV, January, 1998.

First International Conference on Unconventional Models of Computation, Auckland, New Zealand, January, 1998.

Australasian Conference on Structural Optimisation, Sydney, Australia, February, 1998.

Copper Mountain Conference on Iterative Methods, Copper Mountain, CO, March, 1998.

39th AIAA/ASME/ASCE/AHS/ASC, Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, April 20-23, 1998.

1998 American Control Conference, Philadelphia, PA, June, 1998 (2 papers).

1998 International Conference on Parallel Processing, Minneapolis, MN, August, 1998.

Technology transitions or transfer:

PERFORMER
Layne T. Watson, Virginia Polytechnic Institute & State University
Telephone: 540-231-7540
CUSTOMER
General Motors Research and Development Center
Warren, MI
Contact: Alexander P. Morgan, 810-986-2157
RESULT
Homotopy algorithms; mathematical software
APPLICATION
Linkage mechanism design; combustion chemistry; robotics; CAD/CAM

PERFORMER
Layne T. Watson, Virginia Polytechnic Institute & State University
Telephone: 540-231-7540
CUSTOMER
Lucent Technologies
Murray Hill, NJ
Contact: Robert Melville, 908-582-2420
RESULT
Homotopy algorithms; mathematical software
APPLICATION
Circuit design and modelling

PERFORMER
Layne T. Watson, Virginia Polytechnic Institute & State University
Telephone: 540-231-7540
CUSTOMER
Michelin Americas
Greenville, SC
Contact: John Melson, 864-422-4246
RESULT
Adaptive GMRES algorithm; mathematical software
APPLICATION
Iterative solution of large linear systems arising from tire modelling

PERFORMER
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 540-231-5905
CUSTOMER
Sikorsky Aircraft in cooperation with ADOPTech Inc.
Stratford, Connecticut 06497
Sikorsky Contact: Christos Kassapoglou, 203-386-3292
ADOPTech Contact: Grant Soremekun, 540-231-7232
RESULT
Multiobjective genetic algorithms for composite laminate design
APPLICATION
Design of helicopter frame structures for minimum weight and cost

PERFORMER
Zafer Gürdal
Virginia Polytechnic Institute & State University
Telephone: 540-231-5905
CUSTOMER
Boeing Commercial Aircraft
Seattle WA
Contacts: Kumar Bhatia, 425-965-0899 and J. Lynn Henderson, 425-965-0124
RESULT
Demonstrated use of the global/local design methodology to incorporate local laminate details during global sizing
APPLICATION
Fuselage design of a high speed civil transport aircraft

PERFORMER
Raphael T. Haftka, University of Florida
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 352-392-9595 / 540-231-5905
CUSTOMER
McDonnell Douglas Aerospace
Long Beach, CA
Contact: Dr. George Tzong, 310-497-5050
RESULT
Engineering design tool, ADOP + PASCO
APPLICATION
Global/local design of aircraft wing structures

PERFORMER
Raphael T. Haftka, University of Florida
Zafer Gürdal, Virginia Polytechnic Institute & State University
Telephone: 352-392-9595 / 540-231-5905
CUSTOMER
Boeing Computer Services
Huntsville, AL
Contact: Al Underbrink / George P. Williams, Jr., 205-461-2950
RESULT
Installed a genetic optimization code for Huntsville
APPLICATION
Optimal design of racks made of composite laminates for space station

PERFORMER
Raphael T. Haftka, University of Florida
Telephone: 352-392-9595
CUSTOMER
Ford Motor Company
Dearborn, MI
Contact: Dr. Mehran Chirehdast, 313-390-5201
RESULT
Demonstrated application of response surface technology to automotive problems
APPLICATION
Optimal design of automotive structures for increased fatigue life

Inventions or patents.

None.

Honors/awards.

- AIAA Fellow: Raphael T. Haftka.
- AIAA MDO Award: Raphael T. Haftka.
- IEEE Fellow: Layne T. Watson.
- Best Paper Award, Sixth AIAA/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Layne T. Watson.